Historic, Archive Document
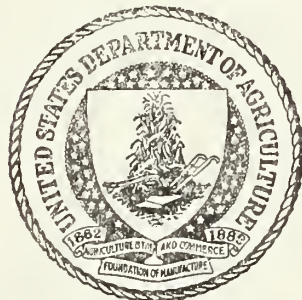
Do not assume content reflects current
scientific knowledge, policies, or practices.

THE ENIGMA OF SOIL NITROGEN BALANCE SHEETS [1]

By

(su rf.) I [2]
F. E. Allison

During the past 50 or more years, many attempts have been made to draw up nitrogen balance sheets for both cropped and uncropped soils. In general, these attempts have met with only mediocre success primarily because quantitative data are usually not available for some of the items that enter into the calculations.

On the side of income, accurate values for additions in the forms of rainfall, irrigation water, seeds, fertilizers, and manures are usually available. However, if legumes are grown, then there are difficulties. The quantity of nitrogen supplied from the air by rhizobia is not likely to be known very accurately under field conditions but can, of course, be determined under special controlled conditions. Or the experimenter may avoid the problem by growing only non-legumes. With regard to nonsymbiotic fixation, we know very little about the quantities supplied under field conditions because they are commonly too small to be measured. Furthermore, any gains may be more than offset by losses.

On the expenditure side of the balance sheet, we have no difficulty in obtaining accurate values for the nitrogen removed in harvested crops and in animals. As for wind and water erosion, these are usually of only minor importance in carefully planned field studies. Leaching, however, presents a major problem. Seldom do we know what values to assign to this source of loss, and there seems to be a wide divergence of opinion among agronomists as to whether such losses are likely to be large or small.

After the balance sheet has been drawn up, we commonly find that income and outgo do not balance even though account has been made of all known soil nitrogen gains and losses. Usually all of the nitrogen that went into the system has not been recovered. It is assumed that some of it has volatilized. Is this true, and, if so, how is it lost and in what quantity? Only on rare occasions does income exceed outgo, if all of the nitrogen added by legumes is considered. This failure of nitrogen balance sheets to balance constitutes the enigma of this discussion. In a broad sense, we are

---

concerned with all items that enter into the nitrogen balance sheet; in other words, there are several enigmas. We shall, however, deal primarily with losses by leaching and volatilization, and in a more limited way, with gains of soil nitrogen from the air through channels other than legumes. Such a discussion of nitrogen balance sheets should give us a better idea of why recoveries of nitrogen in the crop are often only 50% of that added as fertilizer.

Nitrogen Balance Sheet for the Cropped Soils of the United States

When the subject of nitrogen balance sheets is mentioned, we immediately think of the one published in 1936 at New Jersey by Lipman and Conybeare (29). In this study a major attempt was made to account for the income and outgo of soil nitrogen in the United States. A mass of data was assembled and studied, but Lipman emphasized that in many cases quantitative information was inadequate for arriving at accurate values for the quantities of nitrogen gained and lost through the various channels. Lipman's nitrogen balance sheet for our cropped soils is shown on slide 1.

Slide 1. Nitrogen Balance Sheet for Harvested Crop Area of United States - Lipman 1936 (367,554,485 acres)

	Lbs. N per acre per year
Nitrogen additions:	
Rain and irrigation	4.7
Seeds	1.0
Fertilizers	1.7 (7.0 in 1951)
Manures	5.2
Symbiotic N fixation	9.2
Non-symbiotic N fixation	6.0
	27.8
Nitrogen losses:	
Harvested crops	25.1
Erosion	24.2
Leaching	23.0
Volatilization	?
	72.3 +
Net annual loss	44.5 +

This balance sheet is interesting, but it contributes little to the present discussion; because it is incomplete. We need to know the annual decrease in soil nitrogen. Without this figure, we do not know whether all of the nitrogen can or cannot be accounted for; there may have been large losses of nitrogen as gas that are not

mentioned in Lipman's tables. The data do, however, emphasize the large losses due to leaching and erosion. These values should be borne in mind in connection with the later discussion.

A more accurate idea of what is happening to nitrogen in soils can be obtained by studies of individual experiments where soils have been maintained under near-natural conditions, and nitrogen income and outgo measured over a long period of years. In general, such data can be obtained only from lysimeters. Field plot experiments may furnish supplemental information; but, of course, accurate balance sheets cannot be constructed. An occasional pot experiment may also have been performed in such a manner that it supplies valuable information.

Reference will first be made to several lysimeter experiments reported from state experiment stations. The most suitable experiments for this purpose are those:

    1. Where nitrogenous fertilizers, or manures, were
       added in considerable quantity,
    2. Where no legumes were grown,
    3. Where all crops and soils were analyzed, and
    4. Where the experiment was continued for 5 years
       or longer, thereby reducing the errors due to
       soil sampling and analysis. In all such ex-
       periments erosion is, of course, eliminated.

All of the available data that meet the above requirements cannot be discussed in the time available; but representative data from the five experiment stations in this country, where the most work of this type has been done, will be considered.

Lysimeter Experiments

Experiments at Cornell Experiment Station.--During the period since 1910 several lysimeter experiments have been conducted at the Cornell Station. Concrete tanks were filled with layers of soil corresponding to the natural soil horizon.

In one experiment, reported by Bizzell (7), a sandy loam soil was cropped for 15 years with two vegetable crops each year, followed by a winter cover crop. Nitrogen was added in the form of ammonia or nitrate to each vegetable crop at the time of planting. Slide 2 shows the nitrogen balance sheet.

Slide.2. Recovery of Nitrogen from Ammonium Sulfate and Sodium
Nitrate in a 15-year Lysimeter Experiment at Cornell -
Bizzell   (Vegetable crops plus rye cover)

	: Am. sulfate	: Sodium nitrate
	Lbs. N per acre per year*	
Nitrogen sources:		
Rain	6	6
Fertilizer	143	143
Soil loss	31	47
	180	196
Nitrogen recovery:		
Crops	94	110
Leachate	42	46
	136	156
Nitrogen not accounted for	44	40
	% of Available N	
N in crop	52	56
N in leachate	23	23
N not accounted for	24	20

* Averages of 3 replications

It will be observed that there was a marked decrease in soil nitrogen
during the 15-year period even though large quantities were added
each year. Furthermore, only a little more than half of the nitrogen
added or made available from the soil was recovered in the crop.
About half of the remainder was found in the leachate, whereas the
other portion was unaccounted for. It is well to bear in mind that
the loss occurred in a well aerated sandy loam that was fertilized
with excess nitrogen, intensively cultivated, and limed at intervals
to keep the pH near 6.0. J. K. Wilson (58) believed that such losses
are commonly due to loss of nitrite in the exudate from plants, or as
nitrogen gas formed as a result of the reaction of nitrite with amines
in plant juices.

Another interesting Cornell lysimeter experiment using Dunkirk silty
clay loam was reported by Bizzell (3). In this experiment timothy was
grown for 8 years and sodium nitrate in varying amounts was added in
three installments each year. The experimental procedures were

similar to those used in the experiment just discussed. Slide 3 shows the nitrogen balance sheet.

Slide 3. Recovery of Nitrogen in an 8-year Lysimeter Experiment at Cornell - Bizzell   (Continuous timothy)

		Lbs. N per acre per year			
	Nos:	4 & 9:	5 & 10:	6 & 11:	8 & 12
Nitrogen additions:					
Rain		6	6	6	6
Sodium nitrate		213	155	124	93
		219	161	130	99
Nitrogen recovery:					
Crops		154	121	98	78
Leachate		3	2	1	2
Soil gain		17	14	19	15
		174	137	118	95
Nitrogen not accounted for		45	24	12	4

	% of available N			
N in crop	70	75	75	79
N in leachate	1	1	1	2
N not accounted for	21	15	9	4

Under continuous timothy the soil showed a gain of about 16 pounds of nitrogen annually. The crop recovered 70 to 79% of the available nitrogen (fertilizer plus rain). There was almost no loss of nitrogen in the drainage water even where 213 pounds were added annually. The small loss that did occur was in the first year before the timothy was well established. Regardless of this, there was an unaccounted-for loss of nitrogen that varied from a negligible amount at the lowest rate of nitrate addition to 45 pounds per acre per year at the highest rate. Bizzell considered the losses to result chiefly from volatilization.

Experiments at Geneva, New York. -- In 1933 Collison and co-workers (14) reported the results of a 16-year lysimeter experiment at Geneva, New York. In these experiments, where no fertilizer was applied, a soil of low fertility and one that was more productive were used. A nitrogen balance sheet for the lysimeters that were kept in a 4-year, timothy-grain rotation is shown on Slide 4.

Slide 4. Nitrogen Balance Sheet for 16-Year Lysimeter Experiment at Geneva, N. Y. -- Collison (Timothy 2 yrs., barley, wheat)

	Low fertility soil	More fertile soil
	Lbs. N per acre per year *	
Nitrogen sources:		
Rain	9	9
Seed	2	2
Soil loss	52	118
	63	129
Nitrogen recovery:		
Crops	44	69
Leachate	8	14
	52	83
Nitrogen not accounted for	11	46
	% of available N	
N in crop	70	53
N in leachate	13	11
N not accounted for	17	36

*Averages of 2 replications

Both soils lost considerable nitrogen during the 16-year period, and this loss increased as soil fertility increased. It is a little surprising that even though no fertilizer or manure was added, there was a loss of 17 to 36% of the nitrogen available to the crop. This unaccounted-for nitrogen was more than twice the amounts recovered in the drainage waters. The author concludes that the only explanation for the large nitrogen deficits is that nitrogen escapes to the atmosphere.

Experiments at Windsor, Connecticut. -- Rather extensive lysimeter experiments (22, 37, 38, 39), using Merrimac sandy loam, have been reported from the tobacco station at Windsor, Connecticut. In one experiment, various nitrogen sources were applied to tobacco grown continuously for 10 years. The nitrogen recovery data are shown on Slide 5.

Slide 5. Nitrogen Balance Sheet for 10-Year Lysimeter Experiment at Windsor, Conn. -- Morgan (Continuous tobacco)

	Fertilizer Sources				
	Three nitrates	Two + NH$_4$ salts	Two ureas and Cyanamid	Six organis fertilizers	None (1 rep.)
	Lbs. N per acre per year				
Nitrogen sources					
Rain	4	4	4	4	4
Fertilizers	200	200	200	200	0
Soil loss	19	-	-	-	36
	223	204	204	204	40
Nitrogen recovery					
Crops	93	73	88	79	20
Leachate	123	108	88	82	31
Soil gain	-	6	10	19	-
	216	187	186	˙180	51
N not accounted for	7	17	18	24	(11 gain)
	% of available N				
N in crop	42	36	43	39	50
N in leachate	55	53	43	40	78
N not accounted for	3	8	9	12	0

In this experiment with a very sandy soil that was heavily fertilized with nitrogen, it will be observed that usually more of the added nitrogen was recovered in the drainage water than in the crop . Nearly all of the added nitrate was accounted for but there was an average loss of about 10% of the nitrogen added in other forms.

In a similar experiment, calurea was added to cylinders at the rate of 200 pounds of nitrogen per acre per year for 10 years and various cropping systems compared. Slide 6 shows the nitrogen recovery data.

Slide 6. Nitrogen Balance Sheet for 10-Year Lysimeter Experiment
at Windsor, Conn. -- Morgan   (Tobacco or grass)

	Fertilized with Calurea				:No nitrogen	
			:Tobacco:			
			:and oat:	Grass :	:Grass:	
	:Fallow:	Tobacco:	cover :	sod :	:Tobacco:	sod :
			Lbs. N per acre per year*			
Nitrogen sources						
Rain	4	4	4	4	4	4
Fertilizer	200	200	200	190	0	0
Soil loss	67	28	2	-	51	40
	271	232	206	194	55	44
Nitrogen recovery						
Crops	0	90	94	77	19	16
Leachate	225	97	48	28	29	6
Soil gain	--	--	--	8	--	--
	225	187	142	113	48	22
N not accounted for	46	45	64	81	7	22
	% of available N					
N in crop	--	39	46	40	34	36
N in leachate	83	42	23	14	53	14
N not accounted for	17	19	31	42	13	50

* Averages of two replications

The average percentage of added nitrogen plus that released from
the soil that was unaccounted for varied between 17 and 42% for the
fertilized lysimeters, and between 13 and 50% for the unfertilized
soils. It is especially surprising that the lowest recovery was with
grass sod. Most investigators have observed little or no losses with
sod crops and some marked gains have been reported. The recoveries of
added nitrogen were the same where tobacco was grown as where the soil
was kept fallow. In other lysimeters, where mixed sources of nitrogen
were used instead of calurea, the % recoveries were similar. Both the
winter cover crop and grass markedly reduced the nitrogen in the
leachate but did not improve the balance sheet.

Experiments at Knoxville, Tennessee. -- Lysimeter experiments on the
recovery of fertilizer nitrogen from soils have been reported from
the Tennessee Experiment Station. In the two experiments of most
interest in the present discussion, the soils, unfortunately, were
not analyzed at the end of the experiments. The recovery of added
nitrogen must, therefore, be based on the difference between the
nitrogen in the drainage waters from fertilized and unfertilized soils.

In these experiments 989 pounds of nitrogen per acre in the form of
nitrate (36), or of ammonium salts (31) were added in a single
application to an uncropped clay soil in 6-foot lysimeters. Slide 7
gives the results.

Slide 7. Recovery of Nitrogen from Cumberland Silt Loam at
Tennessee — McIntire (Uncropped)

	Nitrogen in drainage waters				
	Total Lbs. per acre	From Fertilizer Lbs. per acre	% recovery	Average % recovery	
First expt.*–5 yrs.					
No treatment	68.3				
Calcium nitrate	889.8	821.5	83.1		
Magnesium nitrate	871.1	802.8	81.2		
Sodium nitrate	987.4	919.1	93.0	85.8	
Second expt.*–12 yrs.					
No treatment	372.8				
Ammonium chloride	1160.1	787.3	79.6		
Ammonium phosphate	1111.3	738.5	74.7		
Ammonium sulfate	1224.7	851.9	86.2	80.2	

*Single additions of 989 lbs. N per acre. 3 replications

The recovery of added nitrate nitrogen averaged 86%, and that of
ammonia nitrogen 80%. Loss of a fair percentage of the nitrogen
by volatilization is indicated.

All of the experiments discussed previously have dealt with soils
in the humid regions. Similar data from the semi-arid and
irrigated regions are sparse. Reference will be made here to only
one such experiment, namely, that at Riverside, California.

Experiment at California Station. -- The experiment at California,
described by Chapman and co-workers (12), and by Broadbent and
Chapman (10), is being conducted in lysimeters that are 10 feet in
diameter and 4 feet deep. These were filled with a Sierra loam top
soil having a nitrogen content of 0.04%. The data for the six
lysimeters that were cropped to Sudan grass for the 15-year period
are given on Slide 8.

Slide 8. Nitrogen Balance Sheet for 15-Year Lysimeter Experiment at California -- Chapman and Broadbent (Sudan grass)

	2.5 tons straw No cover crop			Mustard cover crop turned		
	No N	100 lbs.N	200 lbs.N	No N	100 lbs.N	200 Lbs.N
	Lbs. N per acre per year					
Nitrogen sources						
Rain and irrigation	8	8	9	11	13	13
Fertilizer and straw	32	131	237	0	100	200
Soil loss	96	96	71	120	75	48
	136	235	316	131	188	261
Nitrogen recovery						
Crop	84	140	171	87	139	192
Leachate	51	73	113	18	31	40
	135	213	284	105	170	232
Nitrogen not accounted for	1	22	32	26	18	29
	% of available N					
N in crop	62	60	54	66	74	74
N in leachate	37	31	36	14	16	15
N not accounted for	1	9	10	20	10	11

Nitrogen supplied as calcium nitrate; no replication

In all cases the soil lost much nitrogen and there was failure to account for all of the available nitrogen added or released from the soil. The recovery varied between 80 and 99%. The authors (10) point out that the errors of soil sampling were large. This was due in part to the absence of leaching during the last 5 years of the experiment, which permitted some accumulation and uneven distribution of nitrates. The unaccounted-for nitrogen was presumably volatilized.

In considering lysimeter experiments, it is well to bear in mind that a high degree of accuracy in such experiments is impossible. Chief among the sources of error are the inaccuracies of soil sampling and analysis, and also the errors in the analysis of the leachate. Nevertheless, such experiments do furnish valuable information.

The experiments discussed here bring out the following facts:

1. Crops commonly recovered only 40 to 80% of the nitrogen that was added, or made available, from the soil. Low recoveries were usually obtained where large additions of nitrogen were made, where the soils were very sandy, and where the crop was not adequate to keep the nitrogen low.

2. The nitrogen content of most soils decreased regardless of how much was added as fertilizer unless the soil was kept in uncultivated crops.

3. A large proportion of the nitrogen not recovered in the crop was found in the leachate, but substantial unaccounted-for losses occurred in most lysimeters. Nitrogen gains were few.

4. The magnitude of the unaccounted-for nitrogen was largely independent of the form in which the nitrogen was supplied, whether as nitrate, ammonia, or organic nitrogen.

5. Unaccounted-for nitrogen was commonly slightly higher in cropped soils than in fallow soils. Fifty-one lysimeters that received nitrogen, and were planted to non-legume crops, showed an average loss of 20% of the total available nitrogen; the corresponding figure for 106 uncropped soils was 12%. The average value is near 15%. A small portion of this loss can be accounted for as due to factors, such as insects and birds, loss of leaves and pollen, leaching of nitrogen from the leaves,and failure to determine total nitrogen rather than only nitrates, in the leachate. On the other hand, any nonsymbiotic nitrogen fixation that may have occurred would increase the 15% loss figure. These data constitute strong evidence that nitrogen losses from normal, well-aerated soils, by volatilization, are not negligible.

The statement is frequently made that lysimeter experiments are too artificial to show what happens under normal conditions. Drainage losses seem to be much too high, especially if filled lysimeters are used. Although this criticism is doubtless justified in many cases, this fact does not seriously affect the value of the data for use in the present discussion of the nitrogen balance enigma.

Field Experiments at Rothamsted, England. -- In this connection, data from the Broadbalk wheat fields are of interest because rain gauges are located near the plots. Slide 9, taken from Russell's (47) recent book, gives the pertinent information.

Slide 9. Losses of nitrogen from soils at Rothamsted

| | Broadbalk wheat plots 1865 - 1914 | | | Drain gauges 1870-1915, |
| | Plots | | | |
	Plot 3 No Nitrogen	7 & 13 Am.sulfate: P and K	Plot 2 B: Farm manure	uncropped and untreated
	Lbs. N per acre per year			
Nitrogen sources				
Rain and seed	7	7	7	5
Fertilizer or manure	0	86	201	0
Soil loss, top 9 in.	8	3	—	26
	15	96	208	31
Nitrogen recovery				
Crop	17	45	50	—
Leachate	not deter	not deter	not deter	27
Soil gain	——	——	15	—
	17	45	65	27
Nitrogen not accounted for	2 (gain)	51	143	4

No replication

On the wheat field, where no nitrogen was added, the nitrogen in
the crop accounts for all that was added in the rain plus that released
from the soil. There was no appreciable drainage loss under these
conditions of low available nitrogen. Where no crop was grown on a
similar soil in the drainage gauge, practically all of the released
available nitrogen was recovered in the drainage waters. Evidently,
under these conditions if a crop was present, it got the nitrogen;
otherwise it was lost in the drainage. There is no evidence for gaseous
losses of nitrogen at this low nitrogen level, or for nitrogen fixation.
One process could, of course, offset the other.

Where nitrogen was added as fertilizer or manure, the quantity not
accounted for was large. For ammonium sulfate it was about 50% and
for farm manure, at a much higher rate of nitrogen application, it was
near 70%. Most of this unrecovered nitrogen was probably lost by
leaching just as occurs in lysimeter experiments. In addition,
appreciable losses as both ammonia, and as free nitrogen gas, would
be expected from the manured plot, and to a lesser extent from those
receiving ammonium sulfate.

Cylinder Experiment at New Jersey Station

Another interesting set of experiments that serves as a tie-in between
lysimeter and field experiments is the 4-year cylinder experiment (44)
conducted at the New Jersey Station. In these experiments there was
no provision for catching the drainage waters. The subsoil was merely
removed and mixed, the 4-foot cylinders put in place, and the subsoil
replaced. Eight inches of Penn loam topsoil was then added.

One portion of the cylinders was fertilized regularly with
different nitrogen sources, including manure, and cropped to a
5-year rotation of corn, oats, wheat, and timothy. Slide 10 gives
the nitrogen recovery data for both the limed and unlimed series.

Slide 10. Recovery of Nitrogen from 40-year Cylinder
Experiments at New Jersey
(5-year rotation: corn, oats, oats, wheat and timothy)

Nitrogen sources:	Limed (PH 5.7-6.7)					Unlimed (PH 4.1-5.2)				
	No N	Manure	Sod nitrate	Am. sulf.	Dried blood	No N	Manure	Sod nitrate	Am. sulf.	Dried blood
	Lbs. N per acre per year									
Rain	5	5	5	5	5	5	5	5	5	5
Fertilizer or manure	0	129	50	51	50	0	129	50	51	50
Soil loss	62	6	54	42	37	69	19	59	63	66
	67	140	109	98	92	74	153	114	119	121
Nitrogen recovery:	% of available N									
Crop	32	65	61	52	51	21	60	36	26	32
N not accounted for	52	54	44	47	45	72	61	68	78	73

(Brace annotations: limed 49; unlimed 70)

In the limed soils it will be observed that, on the average, slightly more than 50% of the added nitrogen plus that made available from the soil was recovered in the crop. This recovery figure agrees closely with the values commonly obtained in lysimeter experiments. The unrecovered nitrogen was either lost in the drainage water or as gas.

In the unlimed series the crop growth was less than in the presence of lime, and there was a somewhat greater release of nitrogen from the soil. Only about 29% of the available nitrogen was recovered in the crop. This value is even lower than that obtained in the Connecticut lysimeter experiments where much larger quantities were added to a sandy soil cropped to tobacco. Again we assume, as Lipman and Blair (28) had earlier, that most of the unrecovered nitrogen escaped through leaching. Low crop yields, due to high acidity, would of course favor leaching. It is also well to bear in mind that nitrites are very unstable in acid media and at pH values below 5.0 nitrogen may escape readily as nitric oxide. This may have happened to some extent in these New Jersey cylinders.

Other experiments might be mentioned, if time permitted, which, in general, seem to indicate that nitrogen recovery results, obtained in field experiments, are not greatly different from those reported from lysimeters. There is, however, one important difference between experimental data and practical field results that is sometimes overlooked. In most lysimeters, the water that falls on the soil stays there. There is no runoff. Likewise, experimental field plots are usually located on nearly level soil where the runoff is below average. Under practical field conditions, especially where the soil surface is rolling, it would be logical to expect less loss of nitrogen by leaching than the experiments discussed here would indicate. A decreased rate of removal would give the crop more time to assimilate it. On the other hand, it would allow more opportunity for gaseous losses to occur.

Greenhouse Experiments at Beltsville, Maryland

As a supplement to the studies reported above, it is interesting to see what information greenhouse studies can contribute to the solution of the soil nitrogen balance enigma. The ideal experiment for this purpose is one where several applications of nitrogen were made to the same soil, several non-legume crops grown, and all crops and soils analyzed. Few greenhouse experiments, reported in the literature, meet these requirements. Only two, which were conducted by Pinck and co-workers (42, 43) at Beltsville, will be discussed here.

In one of these experiments (42), five successive green manure crops were grown on an Evesboro loamy sand soil to various stages of maturity, and then incorporated with the soil. After each green manure crop a crop of wheat, or Sudan grass, was grown and the tops harvested. Nitrogen in the form of urea was added at different rates, part to the green crop and part to the harvested crop.

When the nitrogen recovery data from all of the treatments are
plotted against total nitrogen added, the results fall near a
straight line. The slope of this line shows that for every unit
of nitrogen added, the unaccounted-for nitrogen amounted to
about 18%. The few small gains of nitrogen at the lower nitrogen
levels may indicate nonsymbiotic fixation but more likely are
merely within the normal experimental error.

In the second greenhouse experiment, reported by the same authors
(13), the technique was similar, except that the green crops were
grown in the field and added to the soil together with urea. A
few pots received applications of urea, sodium nitrate, and
cottonseed meal without additions of plant materials. The total
number of treatments was 33, all in duplicate. Five successive
additions were made and a crop of either wheat or Sudan grass was
grown after each addition of green crop.

The straight-line graph of these data shows that for every unit of
nitrogen added, regardless of its form, the unaccounted-for nitrogen
amounted to about 14%. A smaller loss in this experiment might be
expected since a large percentage of the nitrogen was supplied as
plant materials.

The average loss of 16% of the nitrogen in the two greenhouse
experiments agrees surprisingly closely with the value of 20%
for the cropped lysimeters. In the greenhouse studies there were,
of course, no leachates to collect and analyze. Furthermore, soil
sampling could be done much more accurately. On the other hand,
there was a greater chance for denitrification in the greenhouse due
to possible temporary waterlogging of the soils.

Losses of nitrogen by volatilization. -- Since volatilization is
apparently important and not well understood, we shall consider
this subject in some detail. Such losses may occur through at
least five channels or mechanisms. These are:

  1. As ammonia.
  2. As oxides of nitrogen.
  3. As nitrogen gas by chemical reaction.
  4. As nitrogen gas by bacterial denitrification.
  5. As organic substances from plants.

Losses as ammonia. -- There is essentially universal agreement
among investigators (24, 27, 33, 50, 51, 57) that under suitable
conditions ammonia is rapidly lost from soil by volatilization.
Such losses may amount to 10 to 25% or even more of the ammonia
added or formed. The main established facts are:

  1. Barely detectable losses may occur at pH 6 to 7 but
     they increase markedly at higher pH values.
  2. Losses from wet soils are likely to be small but are
     very high if an alkaline soil, containing much ammonia
     near the surface, is dried.

3. Losses increase with temperature.
4. Losses are greatest in soils of low exchange capacity.
5. Losses may be high where nitrogenous organic materials
    are allowed to decompose on or near the soil surface,
    even if the soil is acid. As the organic materails
    decompose, the ammonia formed raises the pH locally
    and permits volatilization. This partially explains
    the low recoveries in the crop of nitrogen added as
    manure, when it is spread on the soil surface.

Losses of oxides of nitrogen. -- Nitrogen may escape from soils
as either nitric or nitrous oxides under certain limited condi-
tions. Such losses may occur in considerable quantities from
both acid and alkaline soils.

Nitric oxide, as is well known (3, 17, 18, 19, 46, 52), is formed
rapidly from nitrous acid under acid conditions. Such decomposi-
tion of nitrites becomes appreciable at a pH of about 5.0, and
the rate and extent of decomposition are greatly accelerated with
increase in acidity. Most of the nitrio oxide formed is normally
oxidized chemically to nitric acid or is absorbed by soil organic
matter, but some of this gas escapes to the air. This lack of
stability of nitrous acid is doubtless one of the main reasons for
negative nitrogen balance sheets commonly obtained when working
with acid soils. Microorganisms can contribute to this source of
nitrogen loss through the formation of nitrites, but probably do
not produce (56) nitric oxide directly.

Nitrous oxide is also commonly formed in soils, if nitrates are
present and oxygen is very deficient. In well-aerated soils only
traces, if any, of this gas are formed. These facts have been
demonstrated just recently in three separate laboratories, namely,,
at Arizona, California, and Cambridge. Both Adel (1) and Arnold
(6) consider that the soil is the probable source of the nitrous
oxide found in the atmosphere. Wijler and Delwiche (56) found that
under most soil conditions nitrous oxide was the major product of
denitrification. It was, however, readily reduced to free nitrogen
gas in soils of pH7 and above, but not under acid conditions.

Losses as nitrogen gas by chemical reaction. -- Many claims (5, 58)
have been made that in both plant juices and soils nitrous acid
reacts with reduced forms of nitrogen, such as amino acids and
ammonia, to form nitrogen gas. This reaction proceeds rapidly and
quantitatively in a Van Slyke apparatus in the presence of glacial
acetic acid and in an atmosphere of nitric oxide. Recent work
(3, 4, 56) has shown, however, that there is little likelihood that
this reaction occurs to any appreciable extent under conditions
commonly occurring in nature. At pH values where the reaction
can occur at an appreciable rate, namely 5 or lower, conditions
for nitrite formation by both oxidation and reduction are not
favorable. Even if formed, the nitrites are much more likely to

decompose to form nitric oxide than they are to react with amines or ammonia to form nitrogen gas. We must, therefore, conclude that there is no conclusive evidence at present that nitrogen is lost in more than minor quantities from either soils or plants by the Van Slyke reaction.

Losses as nitrogen gas by bacterial denitrification. -- It seems to be generally agreed among soil bacteriologists that most of the gaseous losses of nitrogen from soils, other than as ammonia, are brought about by denitrifying bacteria. These losses occur chiefly as free nitrogen gas and nitrous oxide. Under strictly anaerobic conditions nitrite and nitrate-nitrogen may be almost completely volatilized in a comparatively short time. The experiments reported recently by Jones (25), show this very strikingly. Where sodium nitrate was added to an air-dried soil, which was then brought up to optimum moisture and incubated anaerobically, about 80% of the nitrogen was volatilized in 3 days. Denitrification proceeded almost as fast where the sole source of energy was soil organic matter as where 0.5% sucrose was added. The rate of gas evolution would undoubtedly have been considerably more rapid if fresh soil had been used.

The rapidity with which denitrification occurs can be shown even more strikingly if pure cultures of denitrifying bacteria are used. Using the Warburg respiration technique, for example, quantitative conversion of nitrite nitrogen into gas may be observed during a period of 2 or 3 hours in the absence of oxygen. Where oxygen is present the rate of evolution of nitrogen gas is markedly retarded. For many years it was rather commonly believed that bacterial denitrification occurs only in soils that are completely anaerobic. Several recent papers (9, 11, 15, 34, 48, 56) have, however, generally agreed that although the process is markedly inhibited by oxygen it is not stopped completely. It is not, however, easy to demonstrate nitrogen evolution in soils that are kept well aerated. Neither is it easy to account for all of the nitrogen added even if tracer techniques are used (32, 56). This subject needs further investigation.

Losses as organic substance from plants. -- A few organic substances, such as methylamine, trimethylamine, hydrocyanic acid, and nicotine, are known to be exuded from plants and a portion of these compounds may be lost by volatilization. Nitrates, nitrites, and ammonia, also commonly occur (58) in plant exudates but most of this nitrogen returns to the soil. Data on the quantities of nitrogen lost to the air from plants are meagre but they are believed to be small.

When we consider the various channels through which nitrogen can be volatilized, it is not surprising that soil nitrogen balance sheets often fail to balance. One might almost be tempted to ask why the unaccounted-for nitrogen figures are not higher than the 15% average value previously mentioned for lysimeters. Under

conditions where soils are likely to be less aerobic than they
are in lysimeters, larger gaseous losses would certainly be expected.
In the presence of nitrates this might occur:

1. In rice paddies,
2. In heavy soils that are poorly drained,
3. In normal soils during wet periods, or
4. In normal soils where fresh organic matter is abundant.

Large losses would also be expected as a result of the volatilization
of ammonia from normal soils where the pH is 7 or above, and ammonia
is added, or being formed at a rapid rate.

In this connection it is of interest to refer to the dry land soils
of the United States where leaching rarely occurs. In such regions
it has been shown repeatedly that many of these soils have lost far
more nitrogen during the past 50 years than has been removed in the
crops -- usually 2 to 3 times as much. Presumably most of this loss
has been through volatilization, but positive proof of this is lacking.
Since most of these soils are basic, or only slightly acid, the chief
loss may be as ammonia.

In general, this discussion has emphasized the ease with which nitrogen
is lost from soils. Mineral nitrogen, whether added as fertilizer or
formed from soil organic matter, will not long remain in the soil in
this form. If it is not assimilated by higher plants it will usually
be lost through leaching or by volatilization. Such losses can be
minimized by providing sufficient carbon to combine with it to form
soil organic matter. But even this fixing of the nitrogen by carbon
is only temporary unless there is a permanent change in the agronomic
system that will permit the establishment of a new equilibrium, and a
higher organic matter level.

Gains of Nitrogen from the Air by Means other than Legumes

It would not be well to conclude this discussion of nitrogen balance
sheets without at least a brief reference to some of the enigmas con-
nected with soil gains in nitrogen. So far as the present discussion
is concerned, we can omit nitrogen fixation by legumes, for their
importance in maintaining and increasing soil nitrogen is well appre-
ciated, even if the exact quantity of nitrogen fixed is seldom known.

The chief enigma centers around the question: How important is non-
symbiotic nitrogen fixation in soils? From time to time claims have been
made that under certain conditions, especially in warmer climates,
fixation by free-living bacteria is adequate to meet most or all of the
crop needs indefinitely. There are, however, few, if any, instances
where adequate proof of such statements can be found. At the present
time nearly all workers (23, 40), at least those outside of Russia (2),
seem to consider that the quantity of nitrogen fixed annually in the
average soil by free-living organisms is small. There are some

indications that grasslands may occasionally be an exception
since several workers (20, 26, 30, 35, 45, 54, 55) have re-
ported annual fixations of 20 to 40, and even more, pounds
per acre. Such results are seldom convincing. When a large
fixation is obtained it is likely to be emphasized, whereas
a loss or small gain may scarcely be mentioned. Such negative
results are not uncommon. Nitrogen increases in sod⁸ that
may seem real may be merely apparent because of a variety of
reasons including:

1. Errors of soil sampling and analysis.
2. Inadequate allowance for additions of nitrogen in
   rainfall.
3. Failure to keep the grass free from all legumes.
4. Insufficient protection against the collection of
   extraneous material, especially due to blowing.
5. Lack of certainty that nitrogen is not obtained
   from the subsoil or ground waters.

It is also possible that some ammonia and oxides of nitrogen
may be absorbed from the air as suggested by Ingham (21), and
others. Furthermore, when a grass plot is located along side
of a cultivated plot the marked difference in nitrogen content
of the soils after several years may indicate a fixation that
did not occur.

On the basis of present information we may conclude that, while
there is a possibility that nitrogen fixation in grass sods may
be important, we are not justified in accepting this idea until
we have much more reliable data than are available at present.

Since accurate data on nonsymbiotic nitrogen fixation under
field conditions are not available, an evaluation of the process
must be based chiefly on laboratory data, and on our general know-
ledge of the metabolism and growth requirements of the organisms
involved. Such information would certainly indicate that
Azotobacter fixes little nitrogen under field conditions. This
conclusion is based chiefly on the following facts:

1. Azotobacter seldom occur in large numbers in soils,
   and are usually completely absent from soils that
   are appreciably acid.

2. They have high energy requirements and the energy
   sources must be simple. Crop residues become avail-
   able only as a result of attack by other organisms
   that use most of the energy themselves. Even if
   sugar is supplied under pure culture conditions,
   Azotobacter seldom fixes more than a pound of
   nitrogen per 100 pounds of carbohydrate.

3. Azotobacter do not thrive in the rhizosphere (12), and
   even if they did, the available energy supply for root
   secretions is probably not large.
4. Nitrogen fixation is inhibited by soluble forms of
   nitrogen in the soil.

The growth requirements of the anaerobes would indicate even less
fixation in normal soils than is brought about by Azotobacter.

Nitrogen fixing blue-green algae may be of far greater importance
than Azotobacter under some special conditions. In an environment
such as a rice field, for example, several recent studies (16, 41,
49, 53) show that these organisms are commonly abundant and active
in fixation. They are not, of course, limited by lack of energy
supply, as are the bacteria. They do, however, require much moisture,
a neutral soil, and a fairly warm climate. These growth requirements
would indicate that they are not of great importance in normal soils,
but quantitative data in support of this viewpoint are entirely
lacking.

Concluding Statement

From the facts presented it is obvious that regardless of years of
research, we can seldom draw up a soil nitrogen balance sheet for a
field soil that is accurate. This is, of course, because we usually
lack quantitative data for some of the major items that we know are
involved in the calculations. We lack the data because of the ex-
perimental difficulties encountered in obtaining them. It is impossible,
or at least impractical, to account for all soil gains and losses in a
single experiment conducted under reasonably normal growth conditions.
In order to obtain accurate values for some sources of gains and losses
it is necessary to make the experimental conditions more and more
artificial. We then wonder how closely the data obtained apply under
field conditions.

It would seem, however, that the enigma of soil nitrogen balance
sheets is much less of an enigma now than it was a few years ago. If
the balance sheet doesn't balance it is usually because the nitrogen
values for either leaching or volatilization, or both, are too low.
There is need for more and better experimental data on both sources
of loss. The leaching and erosion losses should be determined for
undisturbed soils under various conditions with respect to soil, crop,
climate, and topography. On the other side of the balance sheet, we
shall also hope for convincing experimental support for the claims
for large fixations of nitrogen in tropical soils and grasslands
through channels other than legumes.

References

1. Adel, A. 1951. Atmospheric nitrous oxide and the nitrogen cycle. Science 113:624.

2. Allison, F. E. 1947. Azotobacter inoculation of crops. I. Historical. Soil Sci. 64:413-429.

3. Allison, F. E., and Doetsch, J. H. 1951. Nitrogen gas production by the reaction of nitrites with amino acids in slightly acidic media. Soil Sci. Soc. Amer. Proc. 15:163-166.

4. Allison, F. E., Doetsch, J. H., and Sterling, L. D. 1952. Nitrogen gas formation by interaction of nitrites and amino acids. Soil Sci. 74:311-314.

5. Allison, F. E., and Sterling, L. D. 1948. Gaseous losses of nitrogen from green plants, II. Plant Physiol. 23:601-608.

6. Arnold, P. W. 1954. Losses of nitrous oxide from soil. Jour. Soil Sci. 5:116-126.

7. Bizzell, J. A. 1943. Lysimeter experiments, V. Comparative effect of ammonium sulfate and sodium nitrate on removal of nitrogen and calcium from the soil. Cornell U. Mem. 252:1-24.

8. Bizzell, J. A. 1944. Lysimeter experiments, VI. The effects of cropping and fertilization on the losses of nitrogen from the soil. Cornell U. Agr. Expt. Sta. Mem. 256:1-14.

9. Broadbent, F. E. 1951. Denitrification in some California soils. Soil Sci. 72:129-137.

10. Broadbent, F. E., and Chapman, H. D. 1950. A lysimeter investigation of gains, losses, and balance of salts and plant nutrients in an irrigated soil. Soil Sci. Soc. Amer. Proc. 14:261-269.

11. Broadbent, F. E., and Stojanovic, B. F. 1952. The effect of partial pressure of oxygen on some soil nitrogen transformations. Soil Sci. Soc. Amer. Proc. 16:359-363.

12. Chapman, H. D., Liebig, G. F., and Rayner, D. S. 1949. A lysimeter investigation of nitrogen gains and losses under various systems of cover cropping and fertilization, and a discussion of error sources. Hilgardia 19:57-128.

13. Clark, F. E. 1948. Azotobacter inoculation of crops: III. Recovery of Azotobacter from the rhizosphere. Soil Sci. 65:193-202.

14. Collison, R. C., Beattie, H. G., and Harlan, J. D. 1933. Lysimeter investigations, III. Mineral and water relations and final nitrogen balance in legume and nonlegume crop rotations for a period of 16 years. New York State Agr. Expt. Sta., Geneva, Tech. Bull. 212:1-81.

15. Corbet, A. S., and Wooldridge, W. R. 1940. The nitrogen cycle in biological systems, 3. Aerobic denitrification in soils. Biochem. Jour. 34:1036-1040.

16. De, P. K., and Sulaiman, M. 1950. Fixation of nitrogen in rice soils by algae as influenced by crop, CO_2, and inorganic substances. Soil Sci. 70:137-151.

17. Fraps, G. S., and Sterges, A. J. 1939. Possible losses of nitrogen from acid soils through the decomposition of nitrites. Soil Sci. 48:175-181.

18. Gerretsen, F. C. 1949. Nitrogen balance and pH changes in some sandy soils as influenced by microbes and plants. Versl. Landbouwk, Onderz. No. 54, 16:1-68.

19. Gerretsen, F. C. 1950. Microbiological transformation of nitrogen and its influence on nitrogen availability in the soil. Trans. 4th Internat. Congr. Soil Sci., Amsterdam, 2:114-117.

20. Hall, A. D. 1905. On the accumulation of fertility by land allowed to run wild. Jour. Agr. Sci. I, Part 2, 241-9.

21. Ingham, G. 1950. Effect of materials absorbed from the atmosphere in maintaining soil fertility. Soil Sci. 70:205-212.

22. Jacobson, H. G. M., Swanson, C. L. W., and Smith, E. 1948. Effect of various fertilizer cations and anions on soil reaction, leaching, nitrification of urea, and related characteristics in an uncropped soil. Soil Sci. 65:437-460.

23. Jensen, H. L. 1950. A survey of biological nitrogen fixation in relation to the world supply of nitrogen. Trans. 4th Internat. Congr. Soil Sci. Amsterdam, I:165.

24. Jewett, T. N. 1942. Loss of ammonia from ammonium sulfate applied to alkaline soils. Soil Sci. 54:401-409.

25. Jones, E. J. 1951. Loss of elemental nitrogen from soils under anaerobic conditions. Soil Sci. 71:193-6.

26. Karraker, P. E., Bortner, C. E., and Fergus, E. N. 1950. Nitrogen balance in lysimeters as affected by growing Kentucky bluegrass and certain legumes separately and together. Ky. Agr. Expt. Sta. Bull. 557:1-16.

27. Lehr, J. J. 1950. Differences in the recovery of nitrogen from ammoniacal and nitrate sources in the reclaimed polders of the Zuyder Zee. Plant and Soil 2:345-358.

28. Lipman, J. G., and Blair, A. W. 1916. Investigations relative to the use of nitrogenous plant-foods, 1898-1912. N. J. Agr. Expt. Sta. Bull. 288:1-126.

29. Lipman, J. G., and Conybeare, A. B. 1936. Preliminary note on the inventory and balance sheet of plant nutrients in the United States. N. J. Agr. Expt. Sta. Bull. 607:1-23.

30. Lyon, T. L., and Wilson, B. D. 1928. Some relations of green manures to the nitrogen of a soil. Cornell Univ. Agr. Expt. Mem. 115:1-29.

31. MacIntire, W. H., Young, J. B., Shaw, W. M., and Robinson, B. 1952. Nitrogen recoveries from applications of ammonium chloride, phosphate, and sulfate and outgo of complementary ions in rain-water leachings through a six-foot soil-subsoil column. Soil Sci. Soc. Amer. Proc. 16:301-306.

32. MacVicar, R., Garman, W. L., and Wall, R. 1951. Studies on nitrogen fertilizer utilization using N^{15}. Soil Sci. Soc. Amer. Proc. 15:265-268.

33. Martin, J. P., and Chapman, H. D. 1951. Volatilization of ammonia from surface-fertilized soils. Soil Sci. 61:25-34.

34. Meiklejohn, Jane. 1940. Aerobic denitrification. Ann. Appl. Biol. 27:558-573.

35. Miller, M. F. 1947. Studies in soil nitrogen and organic matter maintenance. Mo. Agr. Res. Bull. 409:1-32.

36. Mooers, C. A., MacIntire, W. H., and Young, J. B. 1927. The recovery of soil nitrogen under various conditions as measured by lysimeters of different depths. Tenn. Agr. Expt. Sta. Bull. 138:1-30.

37. Morgan, M. F. and Jacobson, H. G. M. 1942. Soil and crop interrelations of various nitrogenous fertilizers. Conn. Agr. Expt. Sta. Bull. 458:269-328.

38. Morgan, M. F., Jacobson, H. G. M. and LeCompte Jr., S. B. 1942. Drainage water losses from a sandy soil as affected by cropping and cover crops. Conn. Agr. Expt. Sta. Bull. 466: 729-759.

39. Morgan, M. F., Jacobson, H. G. M., and Street, O. E. 1942.
The neutralization of acid-forming nitrogenous fertilizers
in relation to nitrogen availability and soil bases. Soil
Sci. 54:127-148.

40. Norman, A. G. 1946. Recent advances in soil microbiology.
Soil Sci. Soc. Amer. Proc. 11:9-15.

41. Okuda, A., and Yamaguchi, M. 1952. Algae and atmospheric
nitrogen fixation in paddy soils. I, II. Mem. Res. Inst. for
Food Sci., Kyoto U., No. 2, 1-14; No. 4, 1-12.

42. Pinck, L. A., Allison, F. E., and Gaddy, V. L. 1948.
Utilization of nitrogen in cropping systems with and without
green manure in the greenhouse. Soil Sci. 66:39-52.

43. Pinck, L. A., Allison, F. E., and Gaddy, V. L. 1948. The
effect of green manure crops of varying carbon-nitrogen ratios
upon nitrogen availability and soil organic matter content.
Jour. Amer. Soc. Agron. 40:237-248.

44. Prince, A. L., Toth, S. J., Blair, A. W., and Bear, F. E. 1941.
Forty-year studies of nitrogen fertilizers. Soil Sci. 52:
247-261.

45. Richardson, H. L. 1938. The nitrogen cycle in grassland soils:
with especial reference to the Rothamsted Park grass experiment.
Jour. Agr. Sci. 28, Part 1:73-121.

46. Robinson, R. H. 1923. Action of sodium nitrite in the soil.
Jour. Agr. Res. 26:1-7.

47. Russell, E. J. 1950. Soil conditions and plant growth. Logmans,
Green and Co., New York, 8th Ed., 635 pp.

48. Sacks, L. E., and Barker, H. A. 1949. The influence of oxygen on
nitrate and nitrite reduction. Jour. Bact. 58:11-22.

49. Singh, R. N. 1942. The fixation of elementary nitrogen by some
of the commonest blue-green algae from the paddy soils of the
United Provinces and Bihar. Ind. Jour. Agr. Sci. 12:743-56.

50. Steenbjerg, F. 1944. Ammonia loss from nitrogen-containing com-
mercial fertilizers when applied to topsoil. Tids, Planteavl.
48:516-43.

51. Tovborg-Jensen, S., and Kjaer, B. 1948. Loss of ammonia by
evaporation from ammonium sulfate applied to soils. Tids.
Planteavl. 51:666-711.

52. Turchin, F. V. 1936. Decomposition of nitrite in soils un-
saturated with bases and the problem of nitrification.
Z. pflanzenernahr., Dungung Bodenk, 43:170-86.

53. Watanabe, A., Nishigaki, S., and Konishi, C. 1951. Effect of nitrogen-fixing blue-green algae on the growth of rice plants. Nature 168:748-9.

54. White, J. W., Holben, F. J., and Richer, A. C. 1945. Maintenance level of nitrogen and organic matter in grassland and cultivated soils over periods of 54 and 72 years. Jour. Amer. Soc. Agron. 37:21-31.

55. Whitt, D. M. 1941. The role of bluegrass in the conservation of the soil and its fertility. Soil Sci. Soc. Amer. Proc. 6: 309-11.

56. Wijler, J., and Delwiche, C. C. 1954. Investigations on the denitrifying process in soil. Plant and Soil V, 155-169.

57. Willis, W. H., and Sturgis, M. B. 1944. Loss of nitrogen from flooded soil as affected by changes in temperature and reaction. Soil Sci. Soc. Amer. Proc. 9:106-113.

58. Wilson, J. K. 1943. Nitrous acid and the loss of nitrogen. Cornell U. Agr. Expt. Sta. Mem. 253:1-36.